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ASTRONOMY AND ASTROPHYSICS

Activity in late-type stars

VI. Optical photometry and UV spectroscopy of the active dMe star, FK Aquarii in late 1983 ★

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Abstract. We present optical photometry and ultraviolet spectroscopy of the Flare/BY Dra star FK Aqr from 1983. From these data we derive the rate of optical energy release in U-band flaring and compare it to four previous epochs. No conclusive evidence of any variation in this rate over an 8-yr interval has been found. No measurable BY Dra variations were present but a comparison with the mean magnitude in 1979 leads us to suggest that spots were present in 1983 but which were uniformly distributed in longitude. A comparison of transition region line fluxes with those recorded in 1979 does not indicate any large changes but the chromospheric Mg II line flux is smaller by about 25%.

Key words: stars: activity of – stars: chromospheres of – stars: flare – stars: late-type – stars: FK Aqr

1. Introduction

The study of late-type stellar activity is a rapidly growing area of modern astrophysics. In addition to well-established optical studies, space-borne instruments have opened up the UV and X-ray regions of the spectrum for the study of extended, hot outer atmospheres, viz. chromospheres and coronae. It has been established that all measures of activity correlate well with one another, e.g. integrated optical flare energy, chromospheric and coronal radiative losses, rotation periods, etc. (Doyle and Butler, 1985). These inter-relationships contain important clues as to the nature of the global energetics of the atmospheres. It is therefore important to build up a database of these quantities to aid such investigations. It is also important to investigate the behaviour of these activity indicators with time to search for evidence of their variation and any evidence for solar-like cycles. Accordingly we have been monitoring the optical flare and spot activity of the dMe flare star, FK Aqr (= Gl 867 A = HD 214479) over a number of years (Byrne, 1979; Byrne and McFarland, 1980; Byrne et al., 1987a; Byrne and Doyle, 1987). To date we have been unable to find any evidence of variation in the rate of energy release by optical flaring such as might be expected from a solar-like cycle. Here we discuss a further determination of this latter quantity which extends the period covered by this programme to 8 yr.

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★ Based, in part, on observations collected with IUE satellite at the ESA Ground Station, Vilspa, Madrid, Spain

With the advent of the International Ultraviolet Explorer (IUE) satellite and its UV spectrograph (Boggess et al., 1979) we have also been able to measure the radiative losses from the outer atmosphere of FK Aqr, both in flares and in its mean quiescent state (Butler et al., 1981; Byrne et al., 1980). In this latter work we have found that FK Aqr's mean global chromospheric and transition region radiative output is greater than that of the Quiet Sun by one and a half orders of magnitude and that this output can increase by more than a factor of two in flares. Here we present further IUE data on FK Aqr.

FK Aqr is a 4.08 day spectroscopic binary of spectral type dM 2e, whose components are of similar mass (Herbig and Moorhead, 1965). Gliese (1969) gives its distance, based on trigonometric parallax, as 8.3 pc. Byrne (1979) showed that FK Aqr is a dMe flare star. Byrne et al. (1987a) confirmed its membership of the BY Dra (spotted) class of variables and concluded that its rotation period was close to 4.39 day.

2. Observations and results

During November 1–14 1983, FK Aqr was monitored for flares using the 0.75 m telescope at the South African Astronomical Observatory's Sutherland observing station. The telescope was equipped with the automated, pulse-counting "Peoples" photometer and a photomultiplier/filter combination approximating to the Kron-Cousins' $UBV(RI)_{KC}$ system. Monitoring was usually carried out by sequencing through U, B, and V filters with a cycle time of close to 15 s but on a few nights U-band data alone was obtained with an integration time of 5 s. The dates and times of flare monitoring will be found in Table 1. The total monitoring time was 14.1 h and in this time 6 flares were recorded, details of which are given in Table 2. Light curves for some of the flares will be found in Fig. 1.

At least once, and often twice, per night FK Aqr and two nearby comparison stars. HD 214046 and HD 214380, were each measured in all five photometric bands. These were transformed to the standard system by reference to nightly measurements of E-region standard stars (Menzies et al., 1980). Mean magnitudes for the comparison stars derived from this photometry are

	V	$B-V$	$U-B$	$(V-R)_{KC}$	$(V-I)_{KC}$
HD 214046	7.536	+1.434	+1.789	+0.758	+1.482
HD 214380	9.188	+0.497	+0.000	+0.314	+0.562
σ	0.009	0.009	0.009	0.019	0.013

Table 1. Dates and times of monitoring FK Aqr for flares. Note that breaks in monitoring of less than 1 min have been ignored

Date (1983)	UT	Mon. time (sec)	Bands
01–02 Nov	20:19–20:25	384	*U*
02–03 Nov	19:50–21:40	6596	*U*
08–09 Nov	19:19–19:49	1774	*UBV*
	19:53–21:01	4126	
09–10 Nov	19:48–20:43	3292	*UBV*
10–11 Nov	19:40–21:46	7550	*UBV*
11–12 Nov	19:05–21:10	7511	*UBV*
12–13 Nov	19:30–21:07	5876	*UBV*
	21:15–21:28	790	
13–14 Nov	19:33–20:39	3951	*UBV*
	20:51–21:27	2543	
14–15 Nov	19:50–21:33	6217	*UBV*
	Total = 50610 s		

Table 2. Details of flares recorded on FK Aqr. Note that the *U*-band energies quoted for the flares of 2 Nov and 13 Nov are lower limits since their light curves are incomplete (cf. Fig. 1). The rise of the 2 Nov flare occurred before the beginning of the observations, while the 13 Nov flare had not returned to the preflare brightness when observations ended

Date 1983	UT Peak light	Energy (10^{31} erg)		
		V	*B*	*U*
2 Nov	19:57:44	–	–	> 30.50
11 Nov	20:21:02	–	3.57	3.37
12 Nov	19:56:41	–	0.48	0.34
	20:54:41	–	–	3.63
13 Nov	19:45:34	3.20	22.50	> 447.00
14 Nov	21:25:25	–	–	1.16

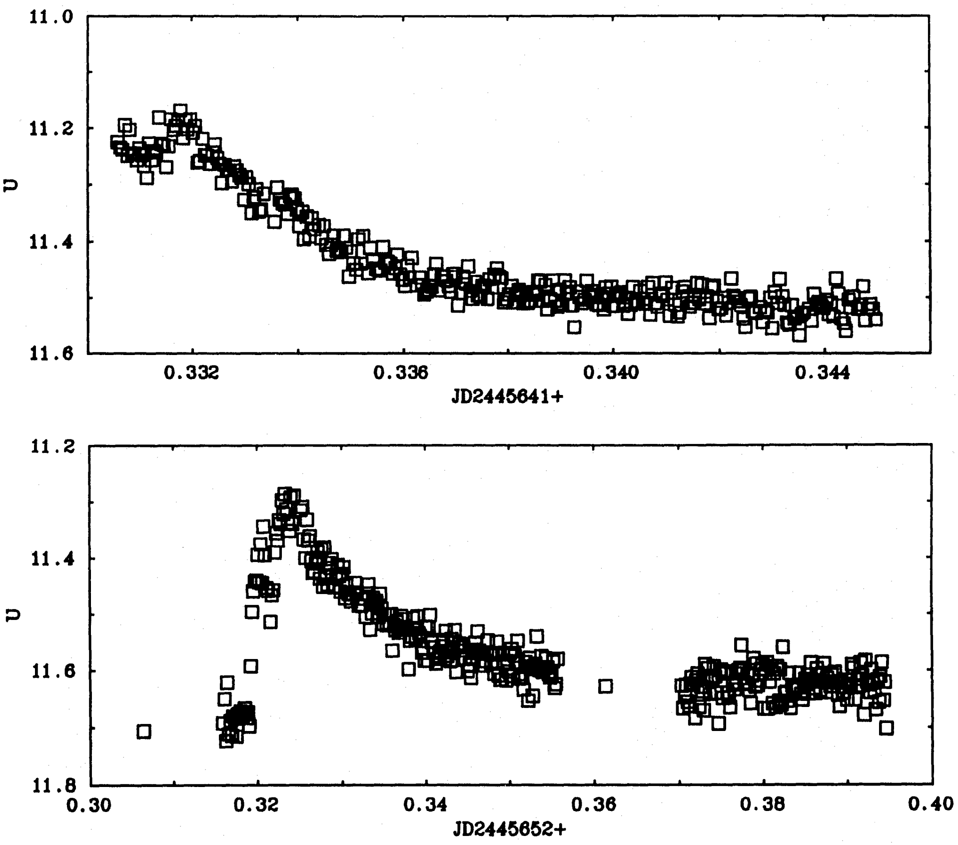

Fig. 1. *U*-band light curves of the two largest flares on FK Aqr on 2 (upper panel) and 13 (lower panel) November 1983

in good agreement with those measured previously (Byrne and McFarland, 1980). We estimate the accuracy of the photometry from the scatter of the nightly means of these stars. This is presented above as a 1σ error. The results for FK Aqr are given in Table 3. A plot of this data against phase, defined by the ephemeris of Byrne et al. (1987a) (Phase = (JD − 2440000.0)/4.39), will be found in Fig. 2.

On two dates in October 1983 (5 and 7) FK Aqr was also observed with the IUE satellite in its low reslution mode. On 5 October spectra were taken alternating between IUE's short (1150–1950 Å; SWP) and long (1900–3200 Å; LWR) wavelength ranges, while the spectrum taken on 7 October was in the SWP range only. Each IUE image usually contained three spectra of equal exposure (30 min for SWP and 8 min for LWR) obtained by moving the star along the spectrograph slit between each exposure. A log of the IUE data will be found in Table 4.

It was not found possible to extract all three spectra independently from each IUE image. Therefore the triple exposures were

Table. 3. Nightly mean $UBV(RI)_{KC}$ for FK Aqr in November 1983. Phases are calculated according to the period of Byrne et al. (1987), i.e. $P = 4.39$ day, and with $JD_0 = 2440000.0$

Date (1983)	Mean JD 2445640.0+	ϕ	V	$(B-V)$	$(U-B)$	$(V-R)_{KC}$	$(V-I)_{KC}$
1/ 2 Nov	0.3425	0.816	9.094	+1.498	+1.168	–	–
2/ 3 Nov	1.2743	0.028	9.092	+1.496	+1.128	+0.974	+2.219
4/ 5 Nov	3.3250	0.496	9.095	+1.480	+1.081	+0.973	+2.218
8/ 9 Nov	7.3368	0.410	9.096	+1.491	+1.094	+0.967	+2.213
9/10 Nov	8.2826	0.625	9.073	+1.503	+1.123	+1.018	+2.215
10/11 Nov	9.3167	0.860	9.088	+1.485	+1.110	+1.004	+2.220
11/12 Nov	10.2792	0.080	9.090	+1.485	+1.105	+1.020	+2.212
12/13 Nov	11.3049	0.313	9.087	+1.488	+1.095	+0.980	+2.178
13/14 Nov	12.3268	0.546	9.091	+1.489	+1.084	+0.986	+2.217
14/15 Nov	13.3076	0.769	9.081	+1.484	+1.108	+0.973	+2.193

Table 4. Dates and times of IUE spectra of FK Aqr. Phases are calculated according to the photometric period of Byrne et al. (1987), i.e. $P = 4.39$ day, and with $JD_0 = 2440000.0$

Date (1983)	UT (mid-exp)	JD (mid-exp) 2445600.0	Phase	Exp (min)	Image no.
5 Oct	16:19:45	13.18038	0.629	90	SWP 21239
	17:44:04	13.23894	0.642	24	LWR 16930
	19:10:23	13.29888	0.656	90	SWP 21240
	20:16:27	13.34476	0.666	24	LWR 16931
	21:20:40	13.38935	0.676	53	SWP 21241
7 Oct	15:39:32	15.15245	0.078	90	SWP 21253

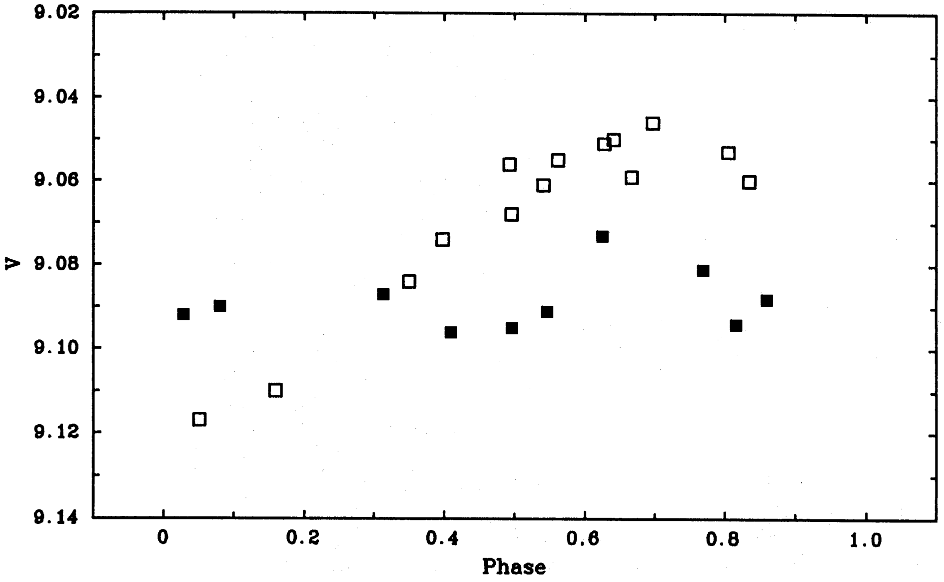

Fig. 2. The V light curve (nightly means) versus phase in November 1983 (filled squares) and the V light curve for August/September 1979 from Byrne et al. (1987a) (open squares). Phases have been determined according to the ephemeris of the latter, i.e. $P = 4.39$ day, and with $JD_0 = 2440000.0$

treated as a single spectrum. The combined spectra were extracted from the IUE images using the IUEDR package (Giddings, 1983) available on the UK STARLINK computer network (Bromage, 1984). The resulting spectra were subjected to a light gaussian smoothing whose FWHM (= 3.5 Å) was less than the resolution of the spectrograph (≈4.5 Å). Sample spectra are shown plotted in Fig. 3. Line fluxes were derived by fitting gaussian functions of instrumental width to the spectra using routines within the DIPSO package (Howarth and Murray, 1987) also available on STARLINK. We have estimated the accuracy of these line fluxes by measuring the amplitude of the background noise in line-free regions of the spectrum. For the SWP spectra this yields

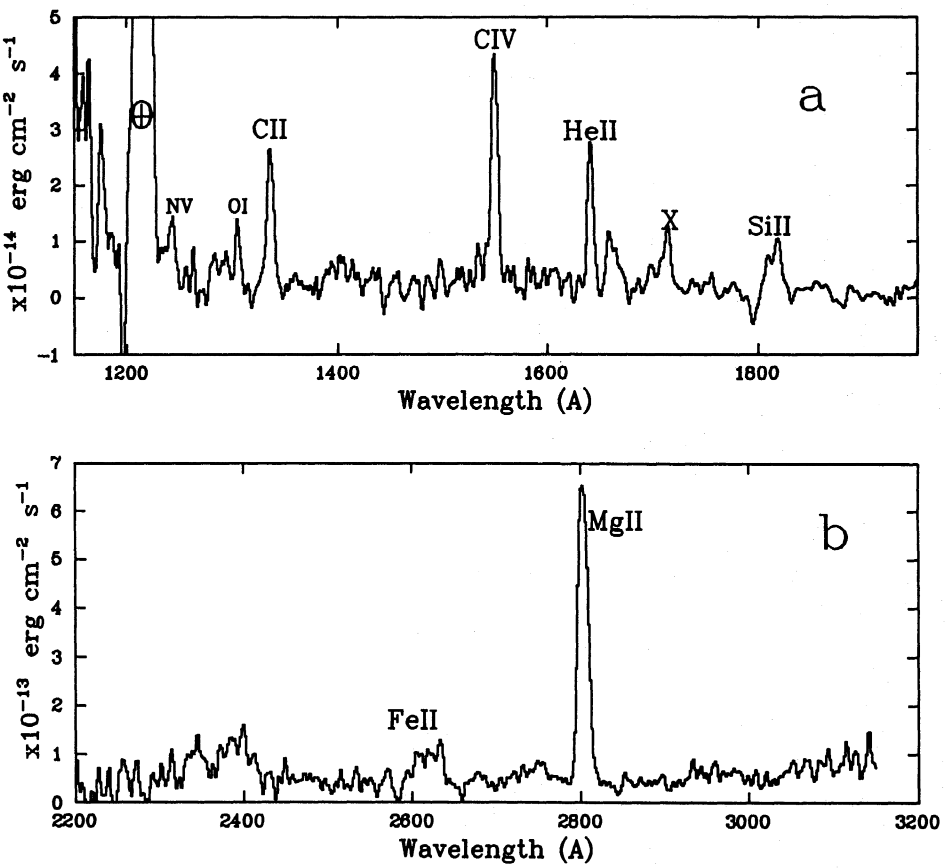

Fig. 3a and b. IUE spectra of FK Aqr in November 1983. **a** The mean quiescent SWP spectrum of 5 October and **b** the mean LWR spectrum on the same date

$\approx \pm 10^{14}$ erg cm^{-2} s^{-1}, for the LWP, $\approx \pm 5\ 10^{14}$ erg cm^{-2} s^{-1}. Line fluxes for the main emission lines in each spectrum will be found in Table 5.

3. Discussion

3.1. Flare energetics

We have calculated the energies of the individual flares using the method of Equivalent Durations (ED), described by Gershberg (1972), and following the method outlined in Byrne (1979). Briefly, we measure, directly from the data, the time taken for the quiescent star to radiate the same amount of energy as that detected in the flare alone, viz.

$$\mathrm{ED} = \sum[(I_{i,f}-I_0)/I_0]\,\Delta t,$$

where I_0 is the mean quiescent intensity, Δt is the time between integrations and the sum is over all points, $I_{i,f}$, in the flare. This method has the advantage of producing a measure of the flare energy which has the dimensions of time and is independent of our knowledge of the quiescent, pre-flare brightness. It may be easily converted to energy once I_0 is known. Flare energies calculated in this way, using the mean quiescent magnitudes for each night from the standard photometry in Table 3 and the calibration of Allen (1973), will be found in Table 2.

Following the methods adopted in the four previous papers on flaring on FK Aqr (Byrne, 1979; Byrne and McFarland, 1980; Byrne et al., 1987a; Byrne and Doyle, 1987), we can estimate the optical flare acitivity parameters, $\langle E_U \rangle$, the mean optical U-band flare energy, and L_U^*, the time-averaged rate of energy release in U-band optical flares. The quantities for the current epoch are

$$\log \langle E_U \rangle = 32.91^{+0.22}_{-0.20}\ \text{(erg)}$$

and

$$\log L_U^* = 28.99^{+0.22}_{-0.20}\ (\text{erg s}^{-1}).$$

All errors have been calculated by assuming Poisson statistics taking into account the asymmetric errors applying to small numbers (Regener, 1951).

These figures are significantly larger than those derived for any individual year analysed previously or for the mean of the four years 1977, 1978, 1979, 1981, viz.

$$\log \langle E_U \rangle = 31.92^{+0.18}_{-0.17}\ \text{(erg)}$$

and

$$\log L_U^* = 27.74^{+0.18}_{-0.17}\ (\text{erg s}^{-1}).$$

These differences in the optical flare rate in 1983 and 1977–81 require further discussion.

There are two obvious differences between the mean flaring behaviour of FK Aqr in 1983 and 1977–81. The first is the difference in $\langle E_U \rangle$ and L_U^* just alluded to. These rates are, however, disproportionately influenced by the single flare of 13 Nov, which was the largest yet observed on FK Aqr. In fact, the U-band energy of the 13 Nov flare represents 92% of the total U-band flare energy observed in the 13.7 h observing reported here and 81% of that observed in 47 h of observing since 1977. Since this is a unique event the rate of such flares cannot be evaluated

Table 5. UV line fluxes from FK Aqr in units of 10^{-13} erg cm^{-2} s^{-1}

Ion (λ)	IUE Image no.				Mean 1983	Mean 1979[a]
	SWP 21239	SWP 21240	SWP 21241	SWP 21253		
N V (1238/42 Å)	1.2	1.3	1.2	1.4	1.3	1.1
O I (1305 Å)	0.8	0.9	0.8	0.9	0.8	0.9
C II (1335/6 Å)	1.9	1.7	2.1	2.0	1.9	1.6
C IV (1548/52 Å)	3.3	3.3	3.5	4.3	3.6	3.2
He II (1640 Å)	1.9	1.9	1.7	1.2	1.7	2.6
C I (1658 Å)	0.7	1.3	1.4	0.8	1.0	1.5
Al II (1671 Å)	0.5	1.0	0.7	–	0.7	–
Si II (1808/17 Å)	1.3	1.7	1.4	1.4	1.3	1.2
	LWP 16930		LWP 16931		Mean (1979)[b]	
Mg II (2796/802 Å)	29.8		29.9		39.9	
Fe II (2600 Å)	36.6		40.7		–	

[a] From Butler et al. (1981)
[b] From Byrne et al. (1980)

and its influence on the mean rate of flare energy release is unknown. We therefore conclude that the previously published rates be adopted unchanged for the present.

The second difference is the rate of occurrence of flares. From the 1977–81 data a mean rate of flaring of $0.24^{+0.12}_{-0.09}\,\mathrm{h}^{-1}$ was recorded with essentially identical observing conditions to those reported in 1983. The expected number of flares in our 13.65 h observing would then be $3.29^{+1.62}_{-1.14}\,\mathrm{h}^{-1}$ compared to the 6 flares observed. Given the previous flare rate, the probability of 6 flares occurring in 13.65 h, assuming Poisson statistics, is 6.6%. This probability is only significant at the 2σ level and so not enough of a deviation to conclude that the rate observed in 1983 is unusual.

3.2. *Spot light curve*

The spot light curve for FK Aqr is shown in Fig. 2. No clear evidence of variation with phase is evident with $\Delta V \geqq 0.01$ or in any of the colours to similar limits. We note however that the mean magnitude in 1983, $V \approx 9.09$, is marginally closer to the minimum observed in 1979 ($V \approx 9.12$) than to the maximum at that epoch ($V \approx 9.03$) (Byrne et al., 1987a). This is illustrated by including the 1979 light curve in Fig. 2. The evidence of the 1983 light curve, therefore, points to one of two conclusions. One possibility is a uniform distribution of spots with longitude, rather than an absence of spots, in the case that the spottedness is concentrated on just one component of the binary. However, since both components of Gl 867A are Balmer emission stars (Herbig and Moorhead, 1965), it is likely that both are chromospherically active and, therefore, spotted. Hence it may be that the absence of spot modulation can be attributed to the relative configuration of the spots on the two components. Nevertheless, since the mean magnitude in 1983 is greater (i.e. the star is globally fainter) than that in 1979, this would suggest that the global spottedness is greater in 1983.

3.3. *UV line fluxes*

The line fluxes measured in the 1983 IUE spectra are presented in Table 5, along with those measured from the mean 1983 spectrum (derived by weighting the individual spectra according to their individual total exposure times) and those from previous IUE spectra of FK Aqr (Byrne et al., 1980; Butler et al., 1981). It is apparent that the overall mean SWP line fluxes in 1983 are very similar to those in 1979 but with C IV (λ 1548/51 Å), C II (λ 1335/6 Å) and C I (1658 Å) perhaps slightly enhanced over the previous values, but He II (λ 1640 Å) being markedly weaker. These differences may be associated with the greater overall spot coverage suggested by the optical light curve. C IV (λ 1548/51 Å) is also enhanced in SWP 21253 which could represent a secular change in the star's output by about 10–20% over the intervening 2 days.

The Mg II fluxes from the two LWR spectra are about 25% smaller than those recorded by Byrne et al. (1980) in 1979. We also note that the total energy in the group of strong Fe II lines near 2600 Å exceed those of Mg II by a similar factor, reinforcing the view of Butler et al. (1987) that Fe II is a very important source of radiative loss from the chromospheres of dMe stars.

From the different behaviour of the various emission lines between 1979 and 1983 it is evident that a greater overall spottedness does not lead in a simpleminded way to a uniform increase in emission line flux as has been suggested elsewhere on the basis of rotational modulation studies (see e.g. Rodono et al., 1987). In fact, Doyle et al. (1989) found that, in the presence of an unusually large spot concentration on the RS CVn system, II Peg, the global IUE emission fluxes actually decreased.

4. Conclusions

We have presented optical photometry and ultraviolet spectroscopy of the Flare/BY Dra star FK Aqr taken in 1983. From these data we have derived the rate of optical energy release in *U*-band flaring and compared it to four previous epochs. We have recorded an increased rate of release of optical flare energy in 1983. However, the increase is only significant at the 2σ level over that expected from a random distribution. Therefore, no conclusive evidence of any variation in this rate over an 8 yr interval has been found. No measurable BY Dra variations were present but a comparison with the mean magnitude in 1979 leads us to suggest that spots, uniformly distributed in longitude, were present in 1983.

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